STUDIES OF ENHANCED EDGE EMISSION OF A LARGE AREA CATHODE*

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Abstract

Electra is a repetitively pulsed, electron beam pumped krypton fluoride (KrF) laser that will be used to develop the technology required for inertial fusion energy (IFE). A full scale fusion KrF laser will be pumped with electron beams with cross-sections of 2,500 to 10,000 cm^2. Understanding the mechanisms that govern uniform electron beam emission over such large areas is important for the overall system efficiency and durability. This paper presents measurements of the current density along the edge of a large area electron beam. The spatial and temporal current density data is obtained with a Faraday cup array at the anode, and the spatial time-integrated current density is obtained with radiachromic film. MAGIC particle-in-cell (PIC) simulations support the experimental results. Experiments and simulations showed that recessing the cathode minimizes the electric field at the edge and eliminates the edge effect.

I.INTRODUCTION

It is well known that the current density is enhanced near the edges of planar explosive emission cathodes. This beam halo is caused by a discontinuity between the vacuum electric field outside the diode (see position 1 of Fig. 1a) and the electric field inside the diode where space-charge dominates the electric field. Recessing the cathode into the metallic shroud to produce a field shaper at the discontinuity reduces the electric field to zero at the triple point [1]. An example of this is shown in Fig. 1b. For relativistic e-beam applications with average electric fields on the order of 100 kV/cm, the elimination of the halo becomes more problematic since electron emission from the electric field shaper must be suppressed.

This research is part of the Electra KrF laser program [2-3] with the goal to develop the technologies needed to produce an efficient and reliable, electron pumped pulsed laser that operates at 5 Hz continuously for 2 years. This investigation is essential to the Electra laser program since a beam edge may cut through the foil that separates the vacuum diode from the high-pressure laser gas. Simply blocking the beam edge with an aperture is not acceptable since this would decrease the overall efficiency.

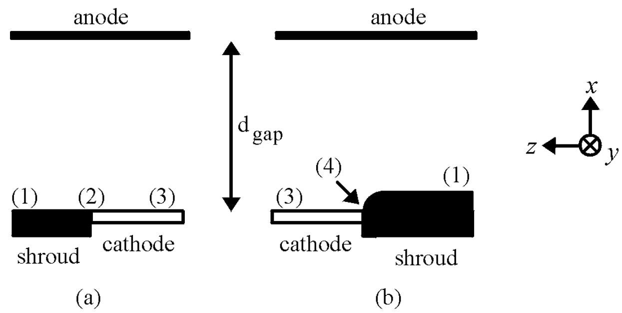

Figure 1. Schematic of the A-K gap. (a) cathode surface is flush with the non-emitting cathode shroud. (1) vacuum electric field, (2) position of the e-beam halo, and (3) $E = 0$ during space-charge limited emission. (b) cathode is recessed to reduce the electric field to zero at position (4).

II.PIC CODE SIMULATIONS

Simulations of the current density along the edge of the electron beam have been performed using the MAGIC [4] 2-D PIC code, developed by Mission Research Corporation, Newington, VA. The cathode size was limited to 10 cm in order to limit the number of cells. For all simulations, a voltage pulse of 500 kV with a risetime of 20 ns was used and the program was stopped after 50 ns when the simulated waveforms reached steady state. An applied axial magnetic flux density of 1.4 kG (0.14 T) was used to prevent pinching of the electron beam in the self-magnetic field. The spatial variation of the current density was observed along the surface of the anode. The following coordinate system is used in this paper: x is the propagation direction of the electron beam, y is the direction along the cathode (e.g., $y_{cathode}$ is 10 cm in the simulations and 27 cm in most of the experimental data), and z is the horizontal direction of the cathode and the direction of propagation of the laser beam (see Fig. 1).

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14. ABSTRACT
Electra is a repetitively pulsed, electron beam pumped krypton fluoride (KrF) laser that will be used to develop the technology required for inertial fusion energy (IFE). A full scale fusion KrF laser will be pumped with electron beams with cross-sections of 2,500 to 10,000 cm2. Understanding the mechanisms that govern uniform electron beam emission over such large areas is important for the overall system efficiency and durability. This paper presents measurements of the current density along the edge of a large area electron beam. The spatial and temporal current density data is obtained with a Faraday cup array at the anode, and the spatial time-integrated current density is obtained with radiachromic film. MAGIC particle-in-cell (PIC) simulations support the experimental results. Experiments and simulations showed that recessing the cathode minimizes the electric field at the edge and eliminates the edge effect.

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Figure 2 shows the dependence of the cathode recess depths *dx* ranging from 0 to 10 mm for a cell grid size of 1 mm. Table 1 provides the peak current density normalized to the Child-Langmuir current density (J_{CL}) for the first five cases. For recesses of more than 5 mm, the beam halo is eliminated but the spatial decrease in current density extends over more than 1 cm. Adequate resolution of the cathode triple point is required to obtain good predictions of the beam halo current density [5] (see Table 2). With finer grid sizes the peak current density (J_{peak}/J_{CL}) is larger than 3 (see Fig. 3) and shows a narrower peak than observed in the experiments. This effect is most likely caused by the simplified modeling of the triple point. The simulations with recessed triple points show only small dependencies with the cell grid size (e.g., J_{peak}/J_{CL} is 1.18 and 1.2 for grid resolutions of 0.5 and 1 mm, respectively). Thus, the PIC code becomes a useful tool for designing the shape of the cathode shroud.

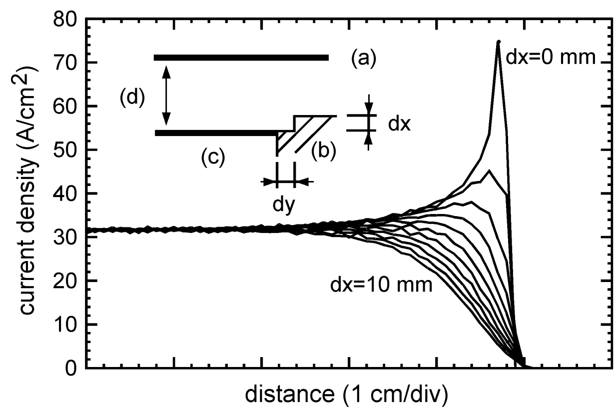

Figure 2. Simulation of the e-beam halo with PIC code grid resolution of 1 mm. (a) anode, (b) metallic non emitting shroud, (c) cathode, and (d) A-K gap of 5 cm, with *dx* ranging from 0 to 10 mm, and *dy* = 1 mm for all cases.

Table 1. Normalized peak current density amplitude for various cathode recess heights as shown in Figure 2.

Cathode recess *dx* (mm)	0	1	2	3	4
Normalized peak current density (J_{peak}/J_{CL})	2.4	1.4	1.2	1.1	1.06

Table 2. Normalized peak current density amplitude as a function of the PIC code grid resolution.

Grid resolution (mm)	0.25	0.5	1.0	2.5	5.0
Normalized peak current density (J_{peak}/J_{CL})	3.2	3.4	2.4	1.8	1.8

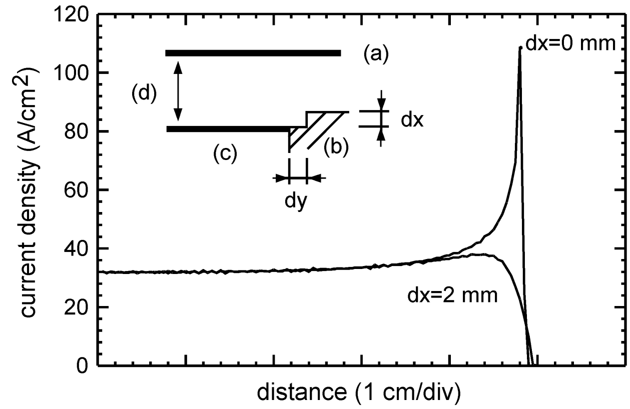

Figure 3. Simulation of the e-beam halo with PIC code grid resolution of 0.5 mm. (a) anode, (b) metallic non emitting shroud, (c) cathode, and (d) A-K gap of 5 cm, and *dy* = 0.5 mm for both cases. The normalized peak current density is 3.4 and 1.18 for *dx* = 0 and 2 mm, respectively.

III. EXPERIMENTAL RESULTS

The basic experimental apparatus has been described previously [2, 6], therefore, it is only briefly summarized here. Two parallel water pulse-forming lines are charged by a capacitor bank that is switched through a 1:12 step-up auto-transformer. Typical operating parameters are 400-550 kV, 70-110 kA, with A-K gaps of 5 to 6 cm. Two cathode sizes (27 x 97 and 35 x 106 cm^2) and various cathode materials have been tested. To prevent pinching, the e-beam is guided through the A-K gap by an axial magnetic field of 1.4 kG that is roughly twice the amplitude of the self-magnetic field at peak current. The anode consists of a 2.5 cm thick aluminum plate covered with 6.3 mm poco graphite and a 25 μm thick aluminized Kapton foil with access ports for diagnostics. In this paper, all experimental results have been obtained with a velvet cathode since this cathode shows the most uniform electron emission [6], and thus, the beam halo effect is clearly observed.

The voltage is measured with a standard capacitive voltage divider near the cathode, the total current is detected with a Rogowski coil, and the e-beam current is sampled with several Faraday cups with a 5 cm beam aperture diameter and B-dot probes as detectors. Fig. 4 shows typical voltage and beam current density waveforms for 27 x 97 cm^2 velvet cathode experiments at 500 kV and an A-K gap of 5.2 cm. This current density has been obtained from a Faraday cup by dividing the measured current by the aperture cross-section.

A. Faraday Cup Array Results

The edge of the electron beam is detected with a Faraday cup array that consists of 8 sensors with an area of 5 x 20 mm^2 each. They are electrically insulated from each other by 76 μm thick Kapton foils, and located on the anode plate. Pearson monitors, model # 2878, measure the collected current of each sensor with a sensitivity of 100 mV/A. The sensor array is placed 13 cm from the central vertical axis of the cathode. The array is positioned vertically so that the lowest sensor element is 3 mm above the cathode (not the beam) edge as shown in Fig. 5, line (a).

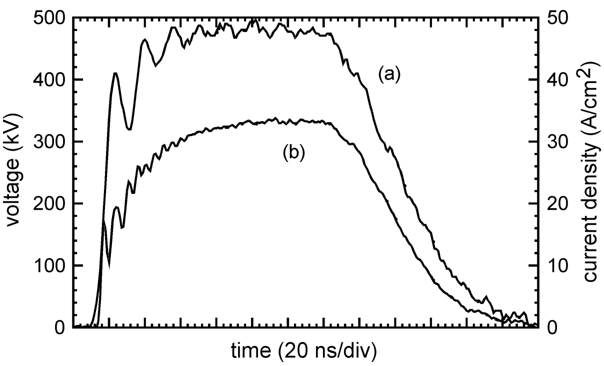

Figure 4. Typical voltage and current density waveforms for velvet cathode experiments. (a) diode voltage and (b) current density waveform near the beam center, with an A-K gap of 5.2 cm.

The self-magnetic field produced by the electron beam current interacts with the applied axial magnetic field and causes the beam to rotate while it travels from the cathode towards the anode. For small rotations, the rotation angle θ_r is given by [7]

$$\tan(\theta_r) = \frac{x}{z}\frac{B_y}{B_x} \tag{1}$$

where x is the beam propagation distance, z is the cathode point horizontal coordinate, B_y is the magnitude of the vertical component of the self-magnetic field, and B_x is the applied magnetic field magnitude. Due to the current rise and fall the rotation angle varies in time, with its maximum value occurring at peak beam current. Lowering the external magnetic field amplitude results in a larger rotation angle as shown in Fig. 5, lines (b) and (c).

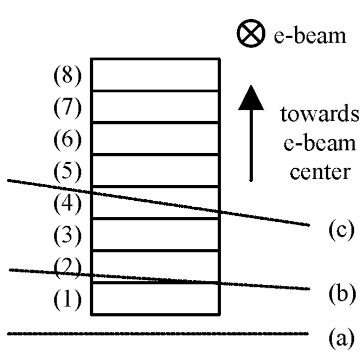

Figure 5. Schematic of the Faraday cup array, overlaid with the position of the e-beam edge as measured by radiachromic film. (a) cathode edge with no rotation, (b) B = 1.4 kG, and (c) B = 0.6 kG. The faraday cups (1) to (8) each have a collector area of 5 mm x 20 mm.

These Faraday cup array results are given in Figs. 6 and 7. The results have been normalized by the peak value of the current density measured at the top three sensors (6 to 8) for the case with B_x = 1.4 kG. The beam halo is clearly detected by Faraday sensors 1 and 2 as shown in Fig. 6. The measured peak amplitude of 1.7 is not the peak of the normalized current density (J_{peak}/J_{CL}) since each sensor averages the current over a vertical height of 5 mm.

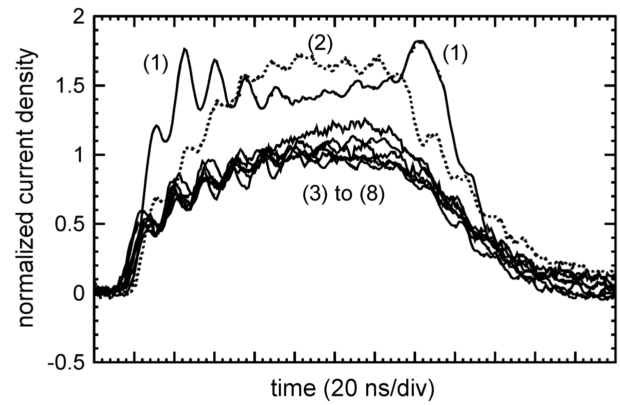

Figure 6. Faraday cup array results with an external magnetic field of B = 1.4 kG. The numbers (1) to (8) correspond to the traces of the individual faraday cups.

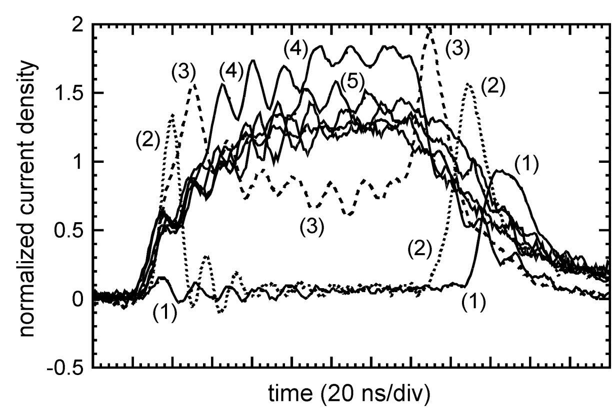

Figure 7. Faraday cup array results with an external magnetic field of B = 0.6 kG. The numbers (1) to (8) correspond to the traces of the individual faraday cups.

When the external magnetic field is lowered to 0.6 kG, the electron beam rotation angle is larger compared to the case with B_x = 1.4 kG. In the middle of the current pulse, the beam halo is located mostly over Faraday cup sensor 4. At that time, both sensors 1 and 2 do not carry any beam current. In addition, the results in Fig. 7 illustrate that during the risetime of the current the beam halo rotates through the bottom four sensors of the array as the self-magnetic field increases with beam current as shown by the individual peaks of sensors 1, 2 and 3 at the beginning of the pulse. The initial peak of sensor 2 is approximately 2.5 times the signal amplitude of sensors 4 to 8, which indicates that the normalized current density of the beam halo (J_{peak}/J_{CL}) is 2.5.

The low initial amplitude peak of sensor 1 indicates that the start of the electron emission at the cathode center is not significantly delayed compared to the emission of the cathode edge (i.e., the rotation angle increases rapidly during the risetime which suggests a large overall beam current). The width of the beam halo can be approximated from individual peaks of sensors 1, 2 and 3 during the fall time of the beam pulse. At that time, the signal of sensor 2 starts to rise while sensor 3 has its maximum current signal. About 20 ns later, at the end of the beam pulse, sensor 1 starts to rise while sensor 2 has its maximum current signal. Thus, the beam halo width should be on the order of 5 mm.

B. Radiachromic Film Results

The time integrated spatial variation of the current density is measured with radiachromic (RC) film. This measurement generates sub-millimeter spatial resolution over a large section of the electron beam (e.g., over the entire vertical height of the cathode and a horizontal width of 15 cm). The film, model number FWT-60 from Far West Technology, is sandwiched between two 25 µm thick titanium foils and placed 3 mm away from the anode. The metal foils prevent exposure of the RC film from ultraviolet photons and low energy plasma electrons. The relativistic electron beam passes through the titanium foil and exposes the RC film. This detector has been calibrated in-situ with adjacent faraday cups. Although the RC film is exposed by the total charge instead of the current density, the rise and fall times and the duration of the current pulse is almost constant for most cases, thus, it is valid to calibrate the film in terms of current density.

Figure 8 shows an example of RC film data. Trace (a) has similar parameters as the PIC simulations presented above. The width of the beam halo is slightly larger than the instantaneous halo because of the beam rotation. The peak of the normalized current density (J_{peak}/J_{CL}) is 2, and this result is a good representation of the beam halo for most parts of the edge (e.g., in some areas along the beam edge small hot-spots with current densities of up to 100 A/cm^2 are detected).

The method of recessing the cathode to eliminate the beam halo has been tested with a larger size cathode that fits directly into the cathode shroud. In that case, the cathode was recessed by 11 mm into the shroud and an electric field shaper was attached to the cathode edge with a similar configuration as shown in Fig. 1b. These results show that the beam halo can be eliminated (see Fig. 8, trace b)

IV. SUMMARY

Using velvet as a reference cathode, experimental measurements and PIC code simulations showed that the edge current density is two to three times the average current density. Reshaping the electric field at the cathode near the triple point reduces the beam halo. Future work will investigate the optimum arrangement that (i) minimizes the electron beam halo effect, (ii) generates an electron beam with a sharp spatial electron density profile, and (iii) contours the field shaper to prevent it from emitting electrons.

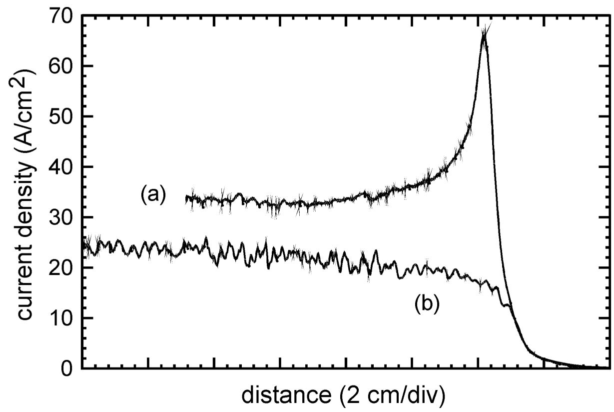

Figure 8. Radiachromic film scan for (a) cathode without recess, V_{diode} = 500 kV, 27 x 97 cm^2 velvet cathode, and (b) cathode recessed into the metal shroud by 11 mm, V_{diode} = 420 kV, 35 x 106 cm^2 velvet cathode. A-K gap = 5.2 cm for both cases.

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